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Effects of white noise on word recall performance and brain activity in healthy adolescents with normal and low auditory working memory

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Abstract

The present study examined the impact of white noise on word recall performance and brain activity in 40 healthy adolescents, split in two groups (normal and low) depending on their auditory working memory capacity (AWMC). Using functional magnetic resonance imaging, participants performed a backward recall task under four different signal-to-noise ratio (SNR) conditions: 15, 10, 5, and 0-dB SNR. Behaviorally, normal AWMC individuals scored significantly higher than low AWMC individuals across noise levels. Whole-brain analyses showed brain activation not to be statistically different between groups across noise levels. In the normal group, a significant positive relationship was found between performance and number of activated voxels in the right superior frontal gyrus. In the low group, significant positive correlations were found between performance and number of activated voxels in left superior frontal gyrus, left inferior frontal gyrus, and left anterior cingulate cortex. These findings suggest that the strategic structure involved in the enhancement of AWM performance may differ in normal and low AWMC individuals.

Keywords Auditory. Functional MRI. Statistical parametric mapping. Working memory. White noise.

Introduction

It is quite astonishing that we are able to suppress irrelevant noise and focus only on relevant information during a conversation in a noisy environment. This is made possible by the cognitive system that is responsible for the maintenance and manipulation of auditory information, commonly referred to as auditory working memory (AWM) (Kumar et al. 2016). AWM performance has been associated with achievement in reading and mathematics (Rogers et al. 2011). Research suggests that white noise may improve cognitive performance in sub-attentive individuals (Helps et al. 2014) and in those clinically diagnosed with attention deficit hyperactivity disorder (ADHD) (Pickens et al. 2019). This phenomenon, whereby random noise is added to enhance cognitive function, is commonly referred to as stochastic resonance (SR) (Moss et al. 2004). SR was originally introduced to explain the periodic recurrences of the Earth's ice age (Benzi et al. 1982). SR in biological systems was first demonstrated in a study of crayfish's mechanoreceptor hair cells, whereby external noise enhanced the sensitivity of sensory neurons towards detecting weak signals (Douglass et al. 1993). The term *stochastic facilitation* was proposed to describe SR that occurs in biological systems (McDonnell and Ward 2011). Most recently, studies of stochastic facilitation have begun crossing disciplinary boundaries into human cognitive functions. Of particular interest are findings that white noise has the capacity to facilitate cognitive performance (Angwin et al. 2017; Baijot et al. 2016; Söderlund et al. 2016).

It should be noted that the beneficial effects of white noise may vary across individuals. For instance, it has been demonstrated that white noise greatly improves performance in inattentive and ADHD participants, but show no significant effect on normal participants (Helps et al. 2014; Söderlund et al. 2016). The differential effects of white noise observed across individuals may be explained through a moderate brain arousal model (MBA) (Söderlund and Sikström 2008). The MBA model proposes that individuals differ in their level of intrinsic neural noise. According to this model, inattentive and ADHD individuals have suboptimal levels of intrinsic neural noise that affect their cognitive performance. In such cases, it has been postulated that adding external noise via the perceptual system could increase the neural noise level, and possibly result in enhanced cognitive performance (Sejdić and Lipsitz 2013). Therefore, based on this theoretical assumption, external noise may not be as beneficial for normal individuals as they have an optimal level of neural noise (Sikström and Söderlund 2007). This assumption, however, remains controversial as studies support the notion that noise enhances new word learning and word recall in healthy individuals (Angwin et al. 2017; Abdul Manan et al. 2012). Most studies of white noise to date have mainly involved clinical populations, and therefore, less is known on its effects on healthy individuals. More importantly, individual differences in auditory working memory capacity (AWMC) have been shown to mediate cognitive performance (Gordon-Salant and Cole 2016). For example, it has been shown that low AWMC individuals score significantly lower than normal AWMC individuals in an auditory stream segregation task (Lotfi et al. 2016). It is, therefore, possible that low AWMC individuals may also have a suboptimal level of intrinsic neural noise. However, to date, there have only been a few studies that have attempted to investigate the effects of white noise in healthy individuals with differences in AWMC.

The present study extends this line of research by investigating whether white noise may differently facilitate word recall performance in healthy participants with different AWMC. The first objective was to compare behavioral performance between normal and low AWMC individuals under different signal-to-noise ratio (SNR) conditions. We hypothesized that individuals with normal AWMC would have an optimal level of intrinsic neural noise, whereas individuals with low AWMC may have a suboptimal level. If this is correct, the provision of white noise during task should increase performance for the low AWMC group but should have no significant effect on performance in the normal AWMC group. Additionally, due to the reduced level of intrinsic neural noise in low AWMC individuals, it was hypothesized that the optimal white noise level for the low AWMC group would be higher than for the normal AWMC group. A secondary aim was to examine and compare brain activity patterns, specifically in the AWM neural network, between the two groups. We hypothesized that brain activity evoked during the task would be significantly different between groups. A tertiary aim of this study was to correlate behavioral performance and brain activity in both groups (separately) under the various SNR conditions. Additionally, we compared the correlations between groups to determine whether a correlation in one group was significantly more than in the other. It was hypothesized that increased brain activity would be associated with increased behavioral performance (i.e., there would be a significant positive brain-behavior relationship). The novelty of the current study is to bring an understanding of whether white noise produces similar effects in healthy individuals with different AWMC. This is important because white noise may be used beneficially in the future as a non-invasive 'tool' during classroom-based teaching to enhance learning in young, healthy students. Another important aim of this study was to elucidate the neural mechanisms underlying AWM enhancement by measuring blood-oxygen-level-dependent (BOLD) signal using functional magnetic resonance imaging (fMRI).

Methods

Participants

Forty-six healthy volunteers (aged between 18 and 24 years) were initially screened for this study. They were recruited from local higher learning institutions. Only male students were selected to control for the effects of gender (Hill et al. 2014). Participants were all native Malay speakers, right-handed, and had normal hearing sensitivity for both ears as assessed using a pure tone audiometry test. Their absolute hearing threshold did not exceed 20 dB HL at 250, 500, 1000, 2000, 4000, and 8000 Hertz. From self-report assessments, none of the participants had a previous history of otitis media, neurological disease, or cognitive disorder. They were also non-musician (Du and Zatorre 2017). Each participant was screened for the use of psychoactive medications or stimulants. Written informed consent was obtained from participants prior to the study. This study followed the principles of the 1964 Declaration of Helsinki. The protocol was approved by the Institutional Ethics Committee of Universiti Kebangsaan Malaysia (UKM PPI/111/8/JEP-2017-117) and Malaysia Medical Research and Ethics Committee (NMRR-17-56-33800).

Auditory working memory capacity assessment

A Malay Version of Auditory Verbal Learning Test (MVAVLT) (Jamaluddin et al. 2009) was conducted to systematically assess individual's AWMC. The test was conducted during an individual session inside a quiet sound-treated room that has been installed with soundproofing materials. The experimenter was inside the room with the participants during the test. They sat facing each other at a distance of approximately 1-meter. The test consisted of five trials. In the first trial, participants were presented with a series of 15 words. Each word was read aloud by the experimenter at an approximately 1-second interval. Participants were instructed to recall those words in any order of presentation. The assessment for a particular trial ended when participants were unable to recall any more words. The same test was repeated five times. The words were read in the same order across trials. The maximum score for each trial was 15. The scores were then summed up over all five trials, resulting in a maximum total score of 75. Participants were categorized into two groups based on their accumulative score from trial one to five. Participants who scored within the upper half of the range of MVAVLT scores (scores of 38 to 75) were assigned to the normal AWMC group, whereas those who scored lower (scores of 1 to 37) were assigned to the low AWMC group.

Auditory stimuli

The auditory stimuli (targeted-speech signal and background white noise) were generated and edited using the Audacity® audio recording and editing software, version 2.1.3. The auditory stimuli consisted of a variety of 40 meaningful, but unrelated, familiar Malay words embedded in white noise of different intensity levels. All of the 40 words were concrete words. To ensure consistency throughout the experiment, these words were all bi-syllabic nouns, further matched for phonological similarity. Additionally, exposure and familiarity with the test words were controlled by presenting each word only three times in each condition. To control for the number of phonemes, each word sequence consisted of dissimilar items. The words were pronounced by a native Malay female speaker and were digitally recorded inside a sound-treated room. The recorded audio files were later edited to remove unwanted background and static noises. The intensity level of the targeted-speech signal was adjusted to 60 dB SPL. The intensity level of the background white noise was set at 45, 50, 55, and 60 dB SPL. Thus, the resulting SNR of speech information was 15, 10, 5, and 0-dB SNR, respectively. The sampling rate of the auditory stimulus was 44.1 kHz with 32-bit float. To ensure that audio output produced the same sound level for every participant, sound levels were measured every time the audio file was played using a digital sound level meter.

Experimental task and procedures

A backward recall task (BRT) was used to assess behavioral performance. This task was specifically chosen as it requires maintenance and manipulation of verbal auditory information (Donolato et al. 2017). Participants were required to listen carefully to four consecutive words and immediately recall those words orally in reverse order of presentation. In every sequence, the words stimuli were presented for 4 seconds, and participants were given 4 seconds afterward to respond. To avoid memory or repetition effect, no word sequence was repeated within each condition. Additionally, the order of the word sequences was randomized across conditions. Figure 1 illustrates the experimental task paradigm. The experimental task was first performed in a quiet sound-treated room without the presence of background noise (referred to as the "quiet" condition thereafter) to obtain a baseline behavioral score for every participant. This baseline score was later compared with the score obtained in the noise conditions to determine whether behavioral performance decreased or increased in the presence of noise. The task was performed on a separate day inside a 3 Tesla Siemens Magnetom Verio MRI system equipped with functional imaging capabilities. Participants were equipped with headphones for transmission of binaural auditory stimuli and noise attenuation.

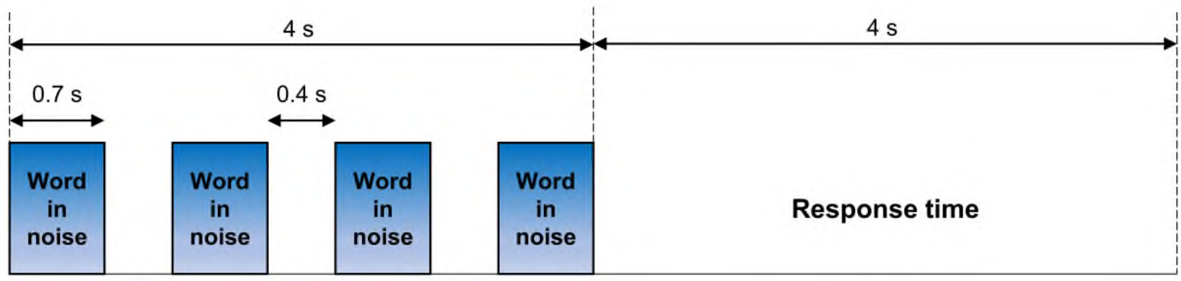

Fig. 1 Stimulus sequence for the BRT. Four consecutive words each with a 0.7-second duration separated by a 0.4-second silent gap, made up a 4-second stimulus train.

fMRI imaging paradigm

A major concern of using fMRI in the context of an auditory study is the loud scanner noise generated from the echo-planar imaging (EPI) pulse sequence during data acquisition. To eliminate the effects of scanner noise, sparse temporal sampling (STS) was used in this study (Hall et al. 1999). STS has a long repetition time, allowing auditory stimuli to be delivered effectively without the contamination of scanner noise during the silent interval between image acquisitions. The BRT consisted of four experimental runs: 15-dB SNR, 10-dB SNR, 5-dB SNR, and 0-dB SNR. The sequence of runs was pseudo-randomized for every participant. Each run, or condition, consisted of 30 stimuli and 30 baseline trials. During the baseline, neither word stimuli nor background white noise was presented. Participants were instructed to rest their mind during this period. Stimuli trials consisted of a 4-second encoding phase (i.e., to-be-remembered words presented auditorily) and followed by a 4-second decoding phase (i.e., overt recall of those words in reverse order of presentation). Functional volumes were acquired immediately following each baseline and stimuli trials. Acquiring functional volumes immediately after the encoding phase would result in mostly measuring brain activity related to storage processing (i.e., maintaining words in mind). The acquired fMRI data would therefore reflect short-term memory instead of AWM. The AWM denotes the ability to temporarily maintain auditory stimuli in mind and to actively perform mental operations on them (Kumar et al. 2016). Therefore, we acquired functional volumes immediately after the verbal response (i.e., manipulation processing). Additionally, we also chose not to acquire functional scans immediately after the presentation of the word stimuli in order to avoid the severe motion artefacts that may arise from giving overt responses. Each run took approximately 10 minutes to complete. In between runs, participants were given two minutes of rest inside the MRI scanner. Figure 2 illustrates the STS imaging paradigm.

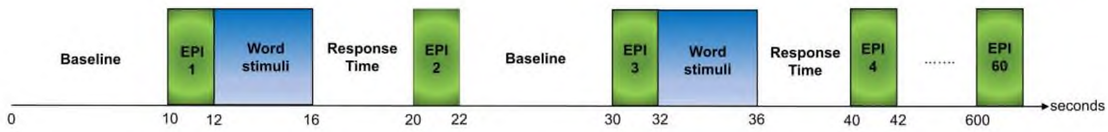

Fig. 2 Schematic representation of the timing diagram for STS.

Data acquisition and pre-processing

Structural images of the entire brain were acquired in high resolution using a T1-weighted multiplanar reconstruction spin-echo pulse sequence. The acquisition parameters were repetition time (TR) = 1900 ms; echo time (TE) = 2.35 ms; flip angle = 9°; voxel size = 1.0 × 1.0 × 1.0 mm; matrix size = 256 × 256. The functional images were acquired using an EPI pulse sequence to produce T2*-weighted images. The acquisition parameters were TR = 10000 ms, TE = 30 ms; acquisition time (TA) = 2000 ms; flip angle = 90º; voxel size = 3.0 mm × 3.0 mm × 5.0 mm; matrix size = 64 × 64. For fMRI, the sparse delay was 8 seconds. Twenty-three transverse slices were acquired parallel to the anterior commissure and posterior commissure plane, in descending order, with no interleave. The total number of active and baseline volumes acquired for all conditions was 240. Functional MRI data were pre-processed using Statistical Parametric Mapping (SPM12) software running on MATLAB 9.13 – R2017b (Mathworks, Natick, MA). The first four EPI scans were discarded to eliminate magnetic saturation effects (Yusoff et al. 2013). The remaining functional images were corrected for slice acquisition delay and realigned to the first image of each session using a six-parameter affine transform to account for head movement in both translational and rotational directions. Head movement thresholds (for exclusion) were set at a maxima of 2 mm for translation and 2° for rotation (Wylie et al. 2014). All participants' head movements did not exceed these thresholds. The data were then normalized to the Montreal Neurological Institute (MNI) brain template using a 12-parameter affine transformation before being spatially smoothed using a 3D Gaussian kernel with full-width at half-maximum of 8-mm. A high pass filter was applied at the cut off frequency of 1/128 Hz to eliminate low-frequency fluctuations.

Data analysis

Demographic and behavioral data were analyzed using IBM Statistical Package for Social Science (SPSS Armonk, NY) version 21 software. The demographic data included age, years of education, and MVAVLT score. The behavioral data included the BRT score obtained by participants across all conditions. The Shapiro-Wilk test was used to assess data normality. An independent sample t-test (P = .05, 95% CI, two-tailed) was conducted to compare the demographic data and BRT scores between the two groups. A one-way repeated measure analysis of variance (ANOVA) was conducted to examine the main effect of noise levels on performance. The whole-brain analysis was conducted using SPM12 to find significantly activated brain areas evoked during the task in noise and to explore patterns of activity across conditions. Individual functional data were analyzed using a first-level fixed-effect analysis (FFX). The following regressors were included in the general linear model design: (i) 15-dB SNR; (ii) 10-dB SNR; (iii) 5-dB SNR (iv) 0-dB SNR; and (v) estimated motion parameters for each participant. The four noise levels were contrasted (separately) against the silent baseline during interstimulus interval, generating statistical parametric maps for the following contrasts: (i) 15-dB SNR > baseline; (ii) 10-dB SNR > baseline; (iii) 5-dB SNR > baseline; and (iv) 0-dB SNR > baseline. These contrasts yielded overall brain activity patterns evoked during word recall in noise minus baseline. The single-subject contrast images were then used in the second-level random-effects analysis (RFX), generating a group statistical parametric map ($P_{FWE} < .05$; with family-wise error correction for multiple comparisons; extent threshold = 0 voxel). All clusters which survived this threshold were regarded as significantly activated cortical brain regions. To identify the group demonstrating significantly greater brain activation, contrast images generated from the RFX analysis for the normal group and the low group were analyzed with a second-level two-sample t-test in SPM12.

A region-of-interest (ROI) analysis was also conducted using WFU PickAtlas (Maldjian et al. 2003) to assess the spatial extent of brain activation (in terms of the number of activated voxels) in a specific set of brain areas (Yusoff et al. 2016). These regions were selected from the literature based on their prominent roles in AWM. The selected regions were superior temporal gyrus (STG) (Buchsbaum et al. 2005), Heschl's gyrus (HG) (Brewer and Barton 2016), superior frontal gyrus (SFG) (Alagapan et al. 2019; Boisgueheneuc et al. 2006; Wegrzyn et al. 2017), middle frontal gyrus (MFG) (Harms et al. 2013), inferior frontal gyrus (IFG) (Hallam et al. 2018; Hirshorn and Thompson-Schill 2006), and anterior cingulate cortex (ACC) (Bryden et al. 2011; Fincham and Anderson 2006; Lavin et al. 2013; Lenartowicz and McIntosh 2005). The ROI analysis was conducted on individual data. A single-subject anatomical atlas (Tzourio-Mazoyer et al. 2002) was used to define image volume masks for each ROI (bilaterally). The mask was then applied onto the individual statistical parametric maps with a statistical threshold of $P_{FWE} < .05$ to obtain activation statistics of the particular regions. The number of activated voxels (NOV) was extracted from the area with the highest T-value (peak MNI coordinate) within the ROI. For each participant, the NOV obtained for every contrast and in each ROI was recorded and Pearson's correlation analysis was conducted to determine whether the NOV was significantly correlated ($P < .05$) with word recall performance in each group separately and contrasted between groups. The differences in correlation between groups were examined by converting the Pearson's correlation coefficient (r) values into z-scores through Fisher Z-transformation. The resulting z-score values were then used to calculate the observed z test statistics (Zobs). The significance level was set at 0.05 (two-tailed). Correlations between groups are not significantly different when the observed z-value falls between -1.96 and +1.96. Bonferroni correction was used for adjustment for multiple comparisons where appropriate.

Results

Demographic data

From the 46 volunteers initially recruited for this study, 25 of the volunteers scored within the upper half of the range of MVAVLT scores (normal group; $n = 25$) and the remaining 21 volunteers scored within the lower half of the range of MVAVLT scores (low group; $n = 21$). Five volunteers from the normal group were excluded from the final sample. Three of them did not come in for the fMRI scan without providing any justification, presumably due to lack of interest or motivation. As for the other two, one withdrew voluntarily and the other one was having an illness, and was, therefore, unable to attend the scanning session. One participant from the low group was also excluded from further participation after feeling extremely anxious and was reluctant to be inside the MRI machine, although he claimed to be non-claustrophobic during the screening process. The final sample consisted of 20 participants in each group. Demographic data for age and years of education are shown in Table 1. The Shapiro-Wilk test for age was non-significant ($P > 0.05$), indicating that age in the normal group ($P = 0.27$) and the low group ($P = 0.10$) was normally distributed. Ideally, due to the effect of aging on AWM performance (Abdul Manan et al. 2014), the mean age between groups should not be significantly different. Result from an independent t-test revealed that this was indeed the case (mean age difference = 0.55 year; $P = 0.278$). Additionally, independent t-test also revealed that the mean years of education between groups was not statistically significant (mean years difference = 0.55 year; $P = 0.278$). The mean years of education in both groups was above nine years, indicating that all participants had a high level of education. It was important that participants shared the same level of educational background as educational level may be a confounding factor on AWMC (Teruya et al. 2009).

Table 1 Demographic data of 40 participants

Description	Normal group	Low group
Auditory working memory capacity	normal	low
Sample size, *n*	20	20
Age in years (mean ± SD)	21.00 ± 1.52	21.55 ± 1.64
Years of education (mean ± SD)	14.00 ± 1.52	14.55 ± 1.64

Cognitive assessment

Participants were categorized into two groups of normal and low AWMC based on their performances in MVAVLT. The accumulative score obtained in trial A1 to A5 were used to determine the participants' AWMC. The results of each trial are tabulated in Table 2. The result of an independent samples t-test indicated that the mean score in the normal group was significantly higher than the one in the low group across trials.

Table 2. Malay Auditory Verbal Learning Test (MVAVLT) scores

Trial	Normal group	Low group	95% Confidence interval of the difference			*P*-value
	(mean ± SD)	(mean ± SD)	Mean difference	Lower	Upper	
A1	7.80 ± 1.01	4.60 ± 0.94	3.20	2.58	3.82	< .001*
A2	8.70 ± 1.17	5.50 ± 1.00	3.20	2.50	3.90	< .001*
A3	9.45 ± 1.36	5.95 ± 1.09	3.50	2.74	4.26	< .001*
A4	10.70 ± 1.30	6.80 ± 0.70	3.90	3.23	4.57	< .001*
A5	12.10 ± 0.83	8.00 ± 0.80	4.05	3.53	4.60	< .001*
Total A1-A5	48.70 ± 4.73	30.85 ± 3.08	17.85	15.35	20.35	< .001*

*Independent samples test is significant at $P < .0085$ (Bonferroni corrected for multiple comparisons).

Behavioral data

The number of correct recalled word sequences (maximum score of 30 per condition) obtained for each group in each condition are tabulated in Table 3. Shapiro-Wilk tests were non-significant ($P > .05$) for all conditions, indicating that the BRT scores were normally distributed. The result from an independent t-test showed that performance in the normal group was significantly higher than that in the low group across conditions. In both groups, ANOVA results revealed significant effects of noise on BRT scores [normal group; $F(4,76) = 118.57$, $P < .001$ and the low group; $F(4,76) = 46.68$, $P < .001$]. The result from the post-hoc pairwise comparison analyses is tabulated in Table 4. The result revealed that, for both groups, performance in the 10 and 5-dB SNR conditions was significantly higher than at baseline ($P < .010$, Bonferroni corrected for multiple comparisons).

Table 3. Backward recall task (BRT) scores

Condition	Normal group (mean ± SD)	Low group (mean ± SD)	95% Confidence interval of the difference			*P* -value
			Mean difference	Lower	Upper	
Quiet	21.20± 1.54	15.15 ± 1.50	6.05	5.08	7.02	< .001*
15-dB SNR	21.90 ± 1.25	17.80 ± 3.09	4.10	2.59	5.61	< .001*
10-dB SNR	24.20 ± 1.64	19.70 ± 4.17	4.50	2.47	6.53	< .001*
5-dB SNR	25.10 ± 1.41	20.15 ± 2.46	4.95	3.67	6.23	< .001*
0-dB SNR	18.55 ± 1.19	10.85 ± 1.81	7.70	6.66	8.74	< .001*

*Independent samples test is significant at $P < .010$ (Bonferroni corrected for multiple comparisons).

Table 4. Post-hoc pairwise comparison analyses

Group	Condition		95% Confidence interval of the difference			*P*-value
	SNR (A)	SNR (B)	Mean difference (A-B)	Lower	Upper	
Normal	15-dB	Quiet	0.70	-0.41	1.81	.591
	10-dB	Quiet	3.00	1.83	4.17	< .001*
	5-dB	Quiet	3.90	2.62	5.18	< .001*
	0-dB	Quiet	-2.65	-4.01	-1.26	< .001*
Low	15-dB	Quiet	2.65	0.05	5.23	.043
	10-dB	Quiet	4.55	1.13	7.97	.005*
	5-dB	Quiet	5.00	2.92	7.09	< .001*
	0-dB	Quiet	-4.30	-6.36	-2.24	< .001*

*Independent samples test is significant at $P < .010$ (Bonferroni corrected for multiple comparisons).

fMRI data

In both groups, results of the second-level random effects group analysis revealed significant activation ($P_{\mathrm{FWE}} < .05$) of bilateral STG, HG, SFG, MFG, IFG, and ACC during the task in four levels of background noise. Additionally, activations of the precentral gyrus, superior parietal lobule, inferior parietal lobule, middle temporal gyrus, insular cortex, claustrum, thalamus, and putamen were also identified. The height extent of activation (*t*-statistics) was higher in the normal group as compared to the low group. However, a direct comparison through a two-sample t-test did not reveal any brain areas significantly differentially activated between groups at a stringent threshold of $P_{\mathrm{FWE}} < .05$. Figure 3 illustrates the brain activation pattern in the normal group and the low group during the task in noise minus baseline.

ROI analyses were conducted to measure the number of activated voxels (NOV) in six ROIs for each participant during the task in noise. Pearson's correlation analysis was later conducted between BRT scores and

NOV in both groups (separately) to examine a possible relationship between performance and brain activity. In the normal group, a significant positive correlation was only found between BRT score and activity (as measured through NOV) in the right SFG during the task in 5-dB SNR (r = .404, P = .039). In the low group, a significant positive correlation was found between BRT score and activity in the left SFG during task in 15-dB SNR (r = .469, P = .037), 10-dB SNR (r = .678, P = .001), and 5-dB SNR (r = .476, P = .034) noise. Similar to that of the left SFG, activity in the left IFG was significantly correlated with BRT score during task in 15-dB (r = .980, P < .001), 10-dB SNR (r = .536, P = .015), and 5-dB SNR (r = .460, P = .041) noise. Activity in the left ACC also showed a significant positive correlation with BRT score during task in 15-dB SNR (r = .478, p = .033), 10-dB SNR (r = .600, P = .005), and 5-dB SNR (r = .464, P = .039). However, after Bonferroni correction for multiple comparisons (P < .004, two-tailed) only the results for the left SFG (10-dB SNR; r = .678, P = .001) and the left IFG (15-dB SNR; r = .980, p < .001) remained significant. Comparisons between correlations were also examined. From the results, only the left IFG result survived after correcting for multiple comparisons. The correlation between activity in the left IFG and BRT score was significantly higher for the low group than the normal group during the task in 15-dB SNR (Zobs = -5.31, P < .001).

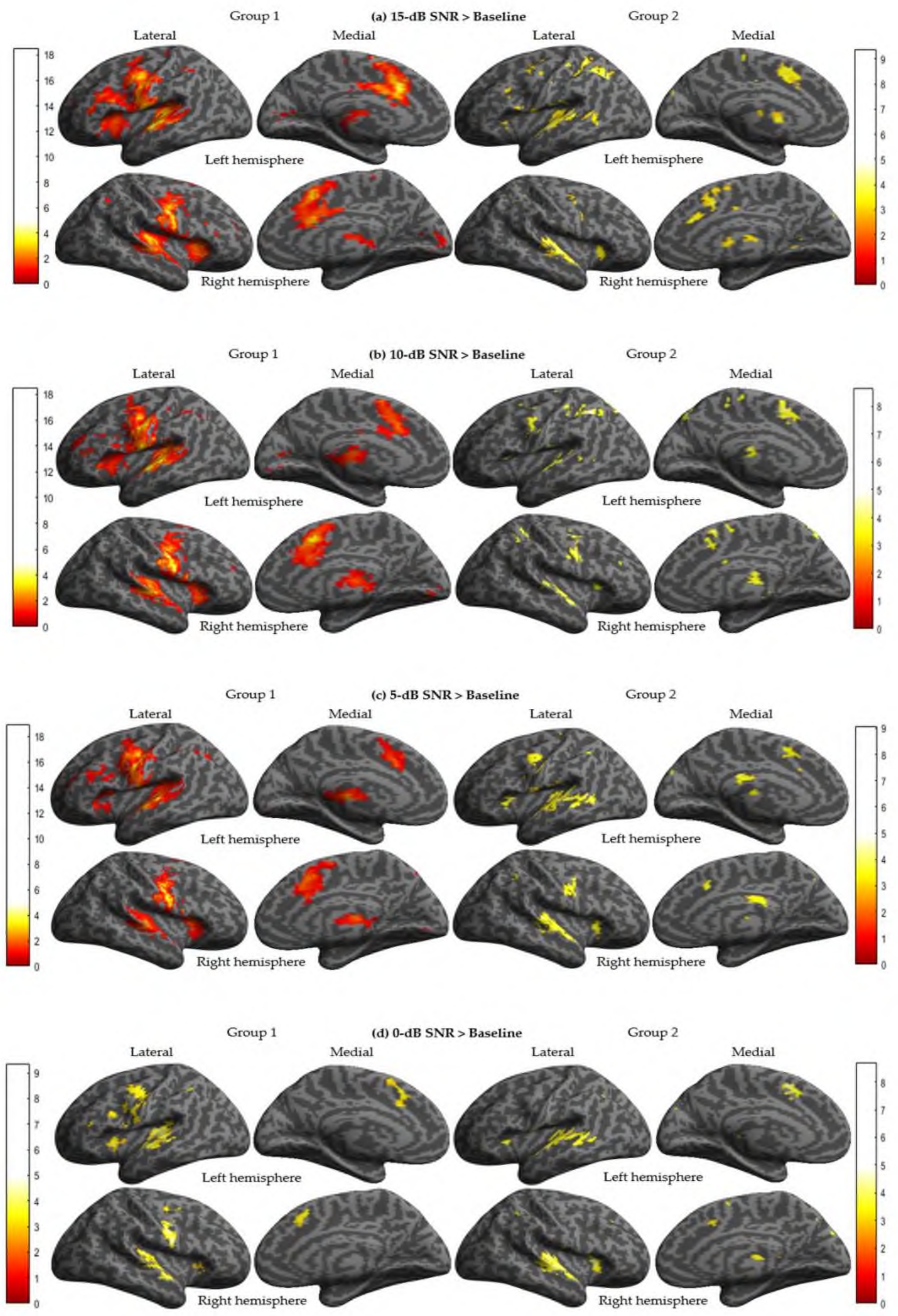

Fig 3. Second-level random effects analyses for 20 participants in the normal group (left panel) and 20 participants in the low group (right panel). The statistical activation maps are thresholded at $P_{\mathrm{FWE}} < .05$, including a correction for multiple comparisons using the family-wise error procedure. The map shows regions with a significantly stronger BOLD-signal during the task in **a** 15-dB SNR, **b** 10-dB SNR, **c** 5-dB SNR, and **d**

0-dB SNR, compared to the baseline condition. The color bar (red to white) indicates the *t*-value for the activated voxels.

Discussion

The main purpose of this study was to examine the effects of white noise on word recall performance in healthy adolescents with different AWMC. Participants were categorized into normal and low AWMC groups based on their performance in the MVAVLT (Jamaluddin et al. 2009). In this test, the first five trials measure the amount of verbal learning and reflect an individual's capacity to actively maintain and retrieve words across trials (Mitrushina et al. 1991; Vakil and Blachstein 1993). The accumulative score from trial A1 to A5, therefore, measures the AWMC (Elst et al. 2005). The results in Table 2 revealed that the accumulative score from trial A1 to A5 in the normal group was significantly higher as compared to the low group. The difference in scores between these two groups may be explained by individual differences in storage capacity. The AWM is considered to have a limited capacity to store and process auditory information (Kumar et al. 2013). Individual differences in AWMC arises from a person's ability to maintain and retrieve information (Unsworth and Engle 2007). They also proposed that individuals with low storage-capacity are poor at keeping things in mind. With regards to the above study (Unsworth and Engle 2007), our findings indicate that normal AWMC individuals have a larger storage-capacity as compared to those with low AWMC. However, it remains unclear if differences in storage-capacity determine AWM performance. The BRT was used to assess the participants' behavioral performance, specifically their AWM performance. The results in Table 3 showed that participants in the normal group were able to accurately recall a significantly higher number of word sequences in the quiet condition as compared to the participants in the low group. This finding suggests that normal AWMC individuals have a good capability for maintaining and manipulating words in their minds as compared to low AWMC individuals. The difference in mean baseline score between the two groups may be due to individual differences in storage capacity (Unsworth and Engle 2007), where the number of items to be stored and processed is determined by the availability of cognitive resources (Joseph et al. 2016).

In contradiction to the traditional belief that noise interferes with working memory performance (Schlittmeier et al. 2015), recent findings see noise as a beneficial 'tool' that can be used effectively to enhance working memory performance (Abdul Manan et al. 2012; Angwin et al. 2017; Baijot et al. 2016; Pickens et al. 2019; Söderlund et al. 2010; 2016). However, the underlying neural mechanism of how noise improves AWM performance has not yet been well-established and demands further investigation. To further elucidate the underlying neural mechanism of AWM processing in adverse acoustics conditions, we conducted our task under four different background noise levels while fMRI data were acquired. A key criterion for this phenomenon to occur is that the background noise level must be optimal (Faisal et al. 2008). The results in Table 4 showed that performance in the normal and low group increased significantly from the baseline score when the task was conducted in 10 and 5-dB SNR conditions. These results indicated that the optimum SNR for both groups were 10-dB SNR and 5-dB SNR. These findings suggest that the optimal level of presentation was 5 to 10 dB SPL below speech.

Based on the aforementioned MBA model (Söderlund and Sikström 2008), we hypothesized that low AWMC individuals would have a reduced level of intrinsic neural noise as compared to normal AWMC individuals and that the low group would require a higher white noise level to compensate for their reduced intrinsic neural noise. The results, however, showed that the optimal SNR to induce stochastic facilitation in the low group was at the same as that of the normal group. If the low AWMC individuals have reduced neural noise, their optimal noise level should have been higher. This finding suggests that low AWMC individuals do not have a reduced level of intrinsic neural noise, as shown in inattentive and ADHD populations (Baijot et al. 2016; Helps et al. 2014; Söderlund et al. 2010; 2016). Our findings also suggest that the level of intrinsic neural noise in healthy individuals do not differ substantially, regardless of their AWM performance. Differences in performance, may, therefore, not necessarily be attributed to individual's level of intrinsic neural noise. Brain activity patterns during the task in noise minus baseline were examined and compared between groups. As illustrated in Figure 3, performing tasks in noise evoked neural responses in bilateral STG, HG, SFG, MFG, IFG, and ACC in both groups. These areas were consistently activated in both groups across noise levels, with the normal group showing a higher height extent of activation as compared to the low group. However, the results of the two-sample t-test did not show a significant difference in brain activation between groups. These results reject our earlier hypothesis that normal AWMC individuals would show stronger activation during the task in noise as compared to low AWMC individuals. This finding may suggest that, despite differences in AWMC, brain functions in healthy adolescents are relatively similar (Emch et al. 2019; Qin and Basak 2020), at least within the context of AWM.

Pearson's correlation analyses were also conducted to identify brain areas that may be strategically involved in the enhancement of AWM performance. Interestingly, regions that showed a significant correlation between performance and brain activity differ between groups. In the normal group, activity in the right SFG was significantly positively correlated with the BRT score during the task in 5-dB SNR. No significant correlation was found in the other noise conditions. The right SFG has been credited to be involved in response inhibition (Wegrzyn et al. 2017). Response inhibition is defined as the ability to suppress actions that interfere with goal-driven behavior, and good inhibitory control has been associated with correct response selection (Mostofsky and Simmonds 2008). However, considering that the correlation was not significant after correcting for multiple comparisons, we are not assured whether improved performance in 5-dB SNR could be attributed to enhanced response inhibition. In the low group, increased activity in the left SFG, IFG, and ACC was associated with increased performance in all SNRs, except 0-dB SNR. It has been proposed that the left SFG plays an important role in the monitoring and manipulation of information (Boisgueheneuc et al. 2006). Increased activity in the left SFG has been associated with improved performance during a verbal working memory task (Alagapan et al. 2019). The left IFG, on the other hand, plays a crucial role in semantic retrieval (Hallam et al. 2018). Increased activity of the left IFG has been associated with higher retrieval success during a working memory task (Hirshorn and Thompson-Schill 2006). The ACC is known for its role in regulating the level of attention (Bryden et al. 2011; Lenartowicz and McIntosh 2005). A previous fMRI study has shown the engagement of ACC in a cognitively demanding task (Lavin et al. 2013). As the experimental task in this study required participants to listen to spoken words attentively, activation of the ACC was expected. Additionally, the task also required participants to control goal-relevance demand constantly (i.e., rearrange words in the reverse order of presentation), and activity in the left ACC has been associated with this (Fincham and Anderson 2006). Based on these findings, it is plausible that white noise at the level below the targeted-speech signal facilitates word recall performance in low AWMC individuals by enhancing the capability to manipulate information, retrieve semantic information, and control goal-relevance demand. However, considering that only activity in the left IFG remained significant (15-dB SNR; r = .980, P < .001) after correcting for multiple comparisons, this claim is open to debate. Thus, it is clear that additional research is warranted to cement or refute such claim.

The current study has several limitations. The sample only included male participants. We cannot, therefore, comment on whether the potential benefits of white noise seen here may produce similar outcomes in healthy female adolescents. The study was also strictly limited by the examination time. The noise levels were therefore limited to only four to avoid having a long examination time. Prolonged scanning duration may cause participants to become restless and consequently result in suboptimal brain activation towards the end of the fMRI scanning session (Yusoff et al. 2016). Therefore, the quiet condition was not performed inside the MRI scanner. Nevertheless, we argue that doing the quiet condition offline did not affect the objective of this study, which was to examine and compare brain activation patterns during the task in noise. However, performing the task outside the MRI environment is different from performing it inside the scanner. This environmental change may have influenced the behavioral results. In terms of homogeneity of the sampling, although the participants shared the same level of educational background, we could not vouch for their intelligence level, which may have affected the results. Another limitation of the study that may potentially have affected the findings was that the participants were divided into normal and low AWMC groups by means of a median split. The disadvantage of using this method is that there may be no distinct differences between subjects near the median. As a consequence, there may be a high potential of overlap between the normal and low AWMC groups. This shortcoming may have contributed to the non-significant results, as activations in one group could have been masked with the other group. The rationale of using the method of the median split is that, to our knowledge, there is no neuropsychological assessment instrument to precisely define individuals with normal and low AWMC. Therefore, this method was adapted from a previous study using a median-split method to categorize individuals with differences in working memory capacity (Gordon-Salant and Cole 2016). Hopefully, there will soon be a reliable and validated neuropsychological assessment instrument to measure AWMC. Future research may extend the current study by including both genders and comparing brain activity during the AWM task in quiet and in the optimal SNR. Additionally, future work may ideally include an intelligence quotient (IQ) test. The present research may also be extended by expanding the battery of cognitive tasks used.

Conclusions

In summary, our study showed that AWMC varies in healthy adolescents and that normal AWMC individuals performed significantly better than low AWMC individuals in word recall tasks across a range of noise conditions. The present study provided further evidence that white noise improved behavioral performance in healthy individuals. We also proposed that differences in performance in healthy individuals are not attributed to differences in the level of intrinsic neural noise as observed in inattentive and ADHD populations. Additionally, the comparison of brain activation did not show a significant difference between groups, suggesting that brain functions among healthy adolescents are relatively similar despite the observed differences in AWMC. However, correlation analyses suggest that the strategic brain regions involved in the enhancement of AWM performance may differ between normal and low AWMC individuals. More importantly, our findings demonstrated that the optimal SNR to induce stochastic facilitation in AWM is 5 to 10 dB SPL below the level of the targeted-speech signal.

Conflicts of interest The authors declare that they have no conflict of interest.

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